MARTIAN METEORITE AGES AND IMPLICATIONS FOR MARTIAN CRATERING HISTORY. L. E. Nyquist, Mail Code KR, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058-3696, laurence.e.nyquist@nasa.gov.

Introduction: New radiometrically determined ages of Martian meteorites add to the growing number with crystallization ages <~ 1.4 Ga. The observation of mainly geologically young ages for the Martian meteorites, the only exception being the ~4.5 Ga ALH84001 [1], is paradoxical when viewed in context of a Martian surface thought to be mostly much older as inferred from the surface density of meteorite craters [2]. There appears to be at least a twofold difference between the observed ages of Martian meteorites and their expected ages as inferred from the ages of Martian surfaces obtained from crater densities.

Recently determined meteorite ages: The crystallization ages of several additional Martian meteorites have been determined since the previous summary [1]. Meteorites for which ages (in Ma) have been determined by the Sm-Nd method include the depleted shergottites Y980459 (472±47 [3]) and NWA1195 (348±19 [4]), basaltic shergottite NWA 856 (171±10 [5]), nakhlites Yamato 000593 (1310±30 [6]) and Mil 03346 (1356±30 [7]), and chassignite NWA2737 (1416±57 [8]). Additionally, new, higher precision Sm-Nd ages have been redetermined for Chassigny (1380±30 [9]), lherzolite Yamato 793605 (156±14 [10]), and basaltic shergottite NWA1460 (345±14 [11]). Essentially concordant Rb-Sr ages also have been determined for NWA 856 (161±5 [5]), Y000593 (1300±20 [6]), Mil 03346 (1294±122, [7]), Y793605 (173±14 [12], and NWA 1460 (336±14 [11]). New, concordant ^{39}Ar-^{40}Ar ages also have been determined for the nakhlites Y000593 (1359±20 [6]) as well as for Chassigny (1338±15 [9]). All of the ~175 Ma basaltic shergottites and lherzolites have significantly higher ^{39}Ar-^{40}Ar ages than the corresponding Rb-Sr and/or Sm-Nd ages due to the presence of excess ^{40}Ar. Because the ^{39}Ar-^{40}Ar ages cited here have been corrected for cosmogenic Ar as well as for trapped Martian atmospheric Ar, some excess ^{40}Ar must have been present in the parental magmas. Although it might be argued that Sm-Nd ages rely heavily on phosphate analyses [13], this is not true of Rb-Sr and ^{39}Ar-^{40}Ar ages. Rb-Sr mineral isochrons are determined by low-Rb/Sr plagioclase and relatively high-Rb/Sr pyroxene and/or melt inclusions in pyroxene, whereas ^{39}Ar-^{40}Ar ages are determined nearly totally by decay of ^{40}K in plagioclase. Thus, the suggestion that the ages may have been reset by percolating fluids [13] cannot apply to the Rb-Sr and ^{39}Ar-^{40}Ar ages.

Sr and Nd isotopic heterogeneity in Zagami:

In spite of overwhelming evidence for young ages of the Martian meteorites, complexities affecting interpretions of their ages long have been apparent. The distinct discordance between Rb-Sr and ^{39}Ar-^{40}Ar ages of Shergotty led [14] and [15] to suggest that the ages were reset by post-shock thermal events. The observation of fine- and coarse-grained lithologies in Zagami [16] inspired an experiment to test for subsolidus isotopic reequilibration. Rb-Sr and Sm-Nd isochrons were simultaneously determined for both lithologies [17]. The resulting isochrons are shown in Figs. 1 and 2. If resetting were diffusion-controlled, it would have been more completely achieved for the fine-grained lithology, but the opposite is observed. This result appears to be evidence that differences in the isotopic composition of relict crystals in a magma mush were incompletely homogenized. Differences were frozen into more rapidly crystallizing fine-grained lithology.

Launch pairing: Cosmic ray exposure ages com-

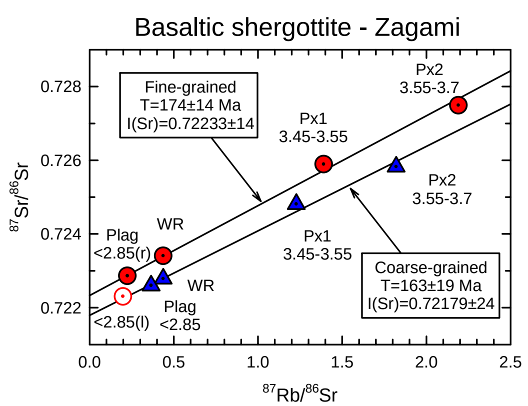

Figure 1. Rb-Sr isochron for minerals from fine- and coarse-grained Zagami lithologies.

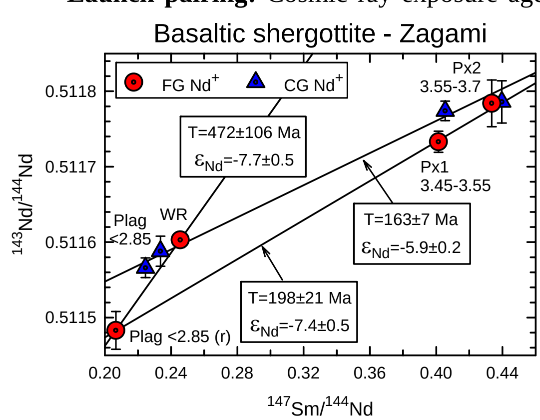

Figure 2. Sm-Nd isochron for minerals from fine- and coarse-grained Zagami lithologies.

bined with terrestrial residence ages are customarily interpreted as dating meteorite ejection from Mars. Recently, Christen et al. [18] identified up to 8 ejection events at 0.7, 1.2, 2.8, 4.1, 10.8, 11.3, 15, and 20 Ma ago for EET79001, olivine-phyric shergottites, basaltic shergottites, lherzolitic shergottites, nakhlites (10.8 Ma), Chassigny (11.3 Ma), ALH84001, and Dhofar 019, respectively. In constructing their Fig, 1, they used the ^{10}Be exposure age of 1.1 Ma [19] for olivine-phyric Yamato 980459 rather than a well-substantiated ^{21}Ne exposure age of 2.9 Ma. The longer ^{21}Ne age was attributed to pre-exposure on the Martian surface, an important example of pre-exposure. The crystallization ages of basaltic and lherzolitic shergottites are the same within error limits (*cf.* Fig. 3), and they may have come from the same event if pre-exposure of some of the lherzolites is allowed. EETA79001 shares the same ~175 Ma crystallization age, suggesting it also may have been launched at the same time, but requiring secondary breakup in space. Finally, the ~330-340 Ma old basaltic shergottites QUE94201 and NWA 1460 share very similar ejection ages of 2.7±0.2 Ma [1], and ~2.6 Ma [19] with ~175 Ma old basaltic shergottites like Zagami (2.8±0.3 Ma [18]). All may have been ejected together from ~340 Ma old terrain.

Meteorite ages compared to surface ages: There are a variety of reasons why the meteorite ages may not be representative of Martian surface ages. The observed lack of impact melt near terrestrial impact craters in sedimentary rock [20] is significant in this regard. Because most Martian sedimentary rocks occur in units of Hesperian age (K. Tanaka, p. comm.), this effect, as well as other hypothesized factors biasing the

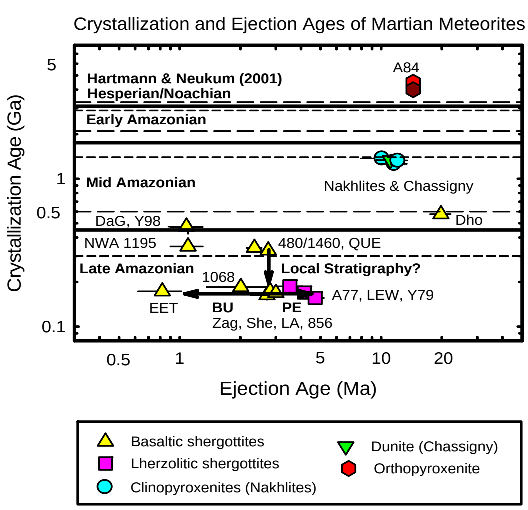

Figure 3. Summary of crystallization and ejection ages of Martian meteorites. Arrows show age variations for local stratigraphy, pre-exposure (PE), and in-space breakups (BU).

meteorite age distribution, applies mostly to Hesperian and older Martian surfaces. However, Hartmann and Neukum [2] set the Hesperian/Amazonian boundary between 2.9 Ga ago (Hartmann system) and 3.3 Ga ago (Neukum system), so even if launches are restricted to the Amazonian, multiple launches should have given some meteorites from the oldest Amazonian terrain; i.e., ~3 Ga old. Thus, the upper limit of 1.4 Ga for Martian meteorites exclusive of ALH84001 suggests a mismatch of a factor two between radiometric and cratering ages (*cf.* Fig. 3).

A 4.0 Ga age for shergottites? ^{207}Pb-^{206}Pb isotopic data for some basaltic shergottites have been interpreted as showing an old, ~4.0 Ga crystallization age for them [13]. This interpretation arises from (a) excluding the Pb isotopic data for magmatic phosphates from the isochron regression, (b) variable initial Pb isotopic compositions in acid resistant minerals, and/or (c) terrestrial contamination [11]. Much of the Pb isotopic data for shergottites are for the major minerals, pyroxene and plagioclase, in the plentiful ~175 Ma basaltic shergottites. The Pb isotopic composition in these minerals of low U/Pb ratios is nearly unevolved from the initial Pb present when the rocks formed. Thus, "isochrons" obtained by combining Pb isotopic analyses of these mineral phases from different meteorites are "mantle isochrons" reflecting the initial ~4.5 Ga differentiation of Mars, not shergottite emplacement.

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